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# Influence of Mainshock-Aftershock Sequence Selection Techniques in Quantifying Seismic Response

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ABSTRACT: Past studies have observed increased vulnerability of the structures when subjected to mainshock-aftershock (MS-AS) ground motion sequences instead of mainshocks (MS) alone. The lack of availability of as-recorded real MS-AS ground motion sequences for the seismic performance assessment of the structure has led to the use of artificially generated sequences. This study aims to quantify the relationship between MS and AS ground motion characteristics in a MS-AS sequence. It also evaluates the need to utilize these relations in developing artificial MS-AS sequences for seismic response evaluation of structures. To this end, a real ground motion database comprising of 192 MS-AS sequences is compiled from different ground motion databases. A univariate and a multivariate linear regression model quantifying the relationship between MS and AS ground motion characteristics in a sequence are developed. Artificial MS-AS sequences are simulated using these regression models. An analytical nonlinear model of four story modern reinforced concrete moment frame building is subjected to sets of real and artificial MS-AS sequences through incremental dynamic analysis (IDA). The IDA results from each set of MS-AS sequences are used to generate seismic collapse fragility curves. The results indicate that the median collapse capacity for the building model calculated using artificial MS-AS sequence set based on regression models developed in the study match closely with the real MS-AS sequence set.

## 1. INTRODUCTION

Buildings located in seismically active regions are subjected to multiple ground shakings from foreshocks, mainshock (MS) and aftershocks (AS) in close proximity, with no time for repair and retrofit of structural damage between the seismic events. For instance, after Gorkha, Nepal earthquake ( $M_w$ 7.8, 2015), more than 100 aftershocks, including $M_w$ 7.3 and $M_w$ 6.3 aftershocks, occurred within one month of the mainshock (Robertson and Koontz 2015). Past studies have concluded that structures are more vulnerable to damage when they are subjected to mainshock-aftershock (MS-AS) ground motion sequences as compared to mainshocks alone due to accumulation of damage over cycles of loading (Gaetani d'Aragona et al. 2017, Raghunandan et al. 2015). This emphasizes the need to use MS-AS sequences in seismic performance studies.

Due to scarcity of as recorded earthquake MS-AS ground motion sequences, artificially generated MS-AS recordings are often used in seismic performance evaluation of structures. For instance, in some studies, artificial MS-AS sequences are generated by randomly appending any MS ground motion as an AS ground motion or by replicating the same MS ground motion as an AS (Lee and Foutch 2004, Raghunandan et al. 2015). However, these artificial sequences do not capture the correlation in ground motion characteristics observed in real MS and AS ground motions in a MS-AS sequence. Past studies have evaluated relationship between some MS-AS sequence characteristics using a limited database of as-recorded MS-AS sequences (Song et al. 2014, Ruiz-Garcia et al. 2011). These studies observed that the use of artificial ground motion sequences, disregarding relationship between MS and AS ground motion parameters in a sequence can result in an unrealistic response estimate of the structure. This highlights the need to develop better models for quantifying the relationship between MS and AS ground motions in a sequence using extensive database of as-recorded MS-AS sequences.

To this end, a real ground motion database comprising 192 MS-AS sequences from different earthquakes is compiled for this study and linear univariate and multivariate regression models quantifying the relationship between MS and AS ground motion parameters in a sequence are developed. MS and AS ground motions in a sequence are selected based on ground motion parameter relationships calculated in the study. The study evaluates the effectiveness of artificial MS-AS sequences in predicting seismic collapse capacity as compared to real MS-AS sequences and other types of artificial MS-AS sequence simulation techniques used in past studies. These findings are demonstrated as a case study for a four story reinforced concrete moment frame developed by Haselton et al. (2011).

## 2. RELATIONSHIP BETWEEN MS AND AS GROUND MOTIONS

### *2.1. Real ground motion sequence database*

Because of few recording stations and rarity of strong earthquake events, there are only few recordings available of MS-AS sequences. A suite of 192 MS-AS sequences from 26 different crustal earthquakes is compiled from different databases (K-NET, KiK-net and PEER NGA–West). In order to mitigate the dominance of a single seismic event on the regression analysis, the maximum number of sequences from a single event is limited to 20 (~10% of the size of the database). The MS-AS ground motion sequences are selected such that both MS and AS events have occurred at the same earthquake fault and in a close proximity of time. The MS and AS ground motions in a sequence are recorded at the same site and orientation. For the unprocessed earthquake ground motions, a first order baseline correction and a fourth order Butterworth band pass filter with the frequency between 0.15Hz-25Hz was employed (Boore and Akkar 2003). The range of magnitude of earthquakes varies from 5.8 to 7.6 for mainshocks and 4.3 to 6.3 for aftershocks. The time elapsed between occurrence of mainshock and an aftershock varies from 7 minutes to 191 days. To minimize the soil structure interaction effect on the structural response, ground motions recorded on soft soils are not considered ( NEHRP site class A-D, ASCE 7-10).

### *2.2. Ground motion parameters*

To quantify the characteristics of MS and AS ground motions in a sequence, 14 different measures of ground motion intensity, frequency content and duration parameters were quantified for all 192 MS and AS ground motions. The ground motion intensity was calculated using the peak ground acceleration (PGA), spectral acceleration at T=1s (Sa(T=1s)) and at fundamental period $T_1$ ($Sa(T_1)$), cumulative absolute velocity (CAV) and Arias intensity ($I_a$). The frequency content of ground motions is calculated using measures such as, central frequency, shape factor, average time period, mean time period, $v_{max}/a_{max}$ , predominant period from Fourier and velocity spectra. The 5-75% and 5-95% significant duration are used as a measure of the duration of earthquake ground motion (Kramer 1996).

### *2.3. Development and validation of regression models*

#### *2.3.1. Univariate linear regression (UVR)*

A simple linear regression analysis is performed for the same parameters of the MS and the corresponding AS ground motion. Among different ground motion parameters, a strong positive correlation is observed between the frequency content parameters of MS and AS ground motions, indicating dependence of aftershock frequency content on the frequency content of mainshock. Figure 1 shows the linear relationship between the central frequency of MS ($\Omega_{MS}$) and AS ($\Omega_{AS}$). Central frequency is calculated as per Vanmarcke (1976) and represents the frequency at which the power spectral density is concentrated . The regression model corresponding to central frequency (Equation 1, Figure 1) was chosen due to higher value of $R^2$ as compared to other models.

$$\Omega_{AS} = 9.248 + 0.828 \times \Omega_{MS} \qquad (1)$$

The low value of p (less than 1% level of significance) in Figure 1 indicates that the slope of the line is significantly different from zero, suggesting a significant correlation between these individual parameters.

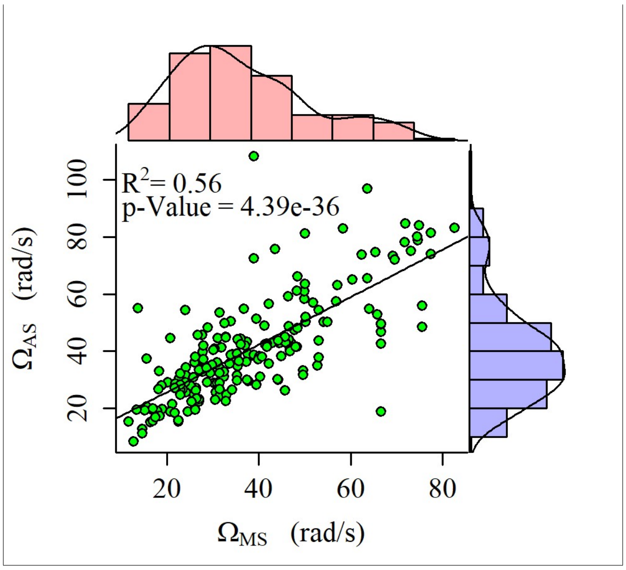


*Figure 1: Scatter plot showing central frequencies of MS and AS in a sequence*

### 2.3.2. *Multivariate linear regression (MVR)*

Univariate regression model provides a simple way to quantify relationship between MS and AS ground motions in a sequence. Despite a good correlation between individual parameters of MS and AS, a more rigorous analysis is required to evaluate the dependence of AS characteristics on multiple MS ground motion characteristics. A multivariate linear regression model with 'n' independent predictor variables is employed as shown below:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \varepsilon \qquad (2)$$

Where $\beta_0, \beta_1, \beta_2, \dots, \beta_n$ are called the regression coefficients and ε is the error term. Y is called the response or dependent variable and $x_1$, $x_2$…, $x_n$ are the predictor or independent variables. Total 14 ground motion parameters described in Section 2.2 are calculated for all 192 mainshock and aftershock ground motions. The Bayesian Information Criterion (BIC) is implemented in order to find the best multivariate linear regression model for each of the 14 AS parameters based on two or more MS predictor variables. The Bayesian Information Criterion (BIC) is formulated as

$$BIC_p = n \ln(SSE) - n \ln(n) + p \ln(n) \qquad (3)$$

Where, p is the number of predictor variables including intercept, n is the number of observations and SSE is the sum of squared errors. The lowest value of Bayesian Information Criterion (BIC) is employed to determine the multivariate regression model for each AS parameter or response variable. Out of all the 14 aftershock response variables, the model with the highest value of coefficient of determination ($R^2$) was selected for the generation of artificial sequences. The properties of that multivariate regression model, which corresponds to central frequency of AS ($\Omega_{AS}$) is displayed in Table 1

*Table 1: Regression model for aftershock central frequency ($\Omega_{AS}$) according to lowest BIC score*

| *Mainshock Predictor Variables ($x_i$)* | *p-Value* | *VIF* |
|---|---|---|
| *Central Frequency($\Omega_{MS}$)* | *$2.2 \times 10^{-33}$* | *1.45* |
| *Shape Factor ($\delta_{MS}$)* | *$7.7 \times 10^{-5}$* | *1.45* |
| $v_{max}/a_{max,MS}$ | *$4.4 \times 10^{-4}$* | *1.93* |

The null hypothesis testing is also performed in order to check whether the slopes of the predictor variables are significantly different from zero. The null hypothesis tested is $H_0$: $\beta_i$=0 and the alternative hypothesis is $H_1$: $\beta_i \neq 0$, where $\beta_i$ is the regression coefficient. The significance level of 0.01 is used. After assuming the null hypothesis to be true, if the obtained p-Value is less than the significance level specified, the null hypothesis is rejected which means the slope or the dependence of the response variable on the given predictor variable is statistically significant in predicting it. It can be deduced from Table 1 that all the predictor variables for the selected multivariate model are statistically significant at 1% significance level (p-Value < 0.01). The regression equations adopted using multivariate linear regression is given in Equation 4.

$$\Omega_{AS} = 19.484 + 0.899 \times \Omega_{MS} - 33.484 \times \delta_{MS} + 76.752 \times v_{max}/a_{max,MS} \qquad (4)$$

Since some parameters of the earthquake ground motion represents same characteristics (intensity, duration, frequency content), a high correlation is observed among some of them. For example, CAV of mainshock ground motions is found to be highly correlated with $I_a$, PGA, $Sa(T_1)$ and Sa(T=1s) of the same ground motion. In order to analyze the level of multicollinearity or correlation between predictor variables of the selected regression model, the variance inflation factors (VIF) are derived. The variance inflation factors for the fitted variables in Equation 4 suggests no significant multicollinearity between them (VIF < 4.0).

## 3. GENERATION OF ARTIFICIAL SEQUENCES

The common approaches involved in generation of artificial sequences are replicated and randomized selection of aftershocks. Either of them does not consider the dependence of aftershock ground motion parameters on those of a mainshock. In order to evaluate the effect of different approaches of aftershock ground motion selection on structural behavior, different sets of 192 MS-AS sequences are prepared. The mainshock ground motions for all the datasets are same and only the aftershocks vary depending upon the approach adopted for selection of aftershock.

- *Set A:* Real MS-AS sequences from Section 2.1.
- *Set B & C:* AS selected for each MS in MS-AS sequence based on AS parameter predicted from Equation 1 (UVR) and Equation 4 (MVR) respectively.
- *Set D:* MS replicated as AS in MS-AS sequence
- *Set E:* Any of the 192 MS randomly paired as AS. Total of 15 sets (E1-E15) were developed in the same manner to have the inference on variability in estimating collapse resistance capacity of structures using this technique.
- *Set F:* Only 192 MS, no aftershocks

For selecting MS-AS sequence in set B&C, a ground motion database of 4126 earthquake ground motions were compiled from PEER NGA-West 2 database. These ground motion records are from crustal earthquakes and are recorded at far-field sites with no soft soil (NEHRP site class A-D). They have a wide range of intensity as well as frequency content and do not contain any ground motions from Set A.

For Set B AS, the central frequency of AS is predicted for each of the 192 mainshocks using Equation 1. The central frequencies of all 4126 ground motions are calculated and the ground motion possessing the central frequency closest to the predicted one is picked from 4126 ground motions and appended after the mainshock to generate MS-AS sequence. The procedure is repeated for each mainshock ground motion resulting in 192 artificially generated MS-AS sequences with employment of univariate linear regression model. Similarly, the AS are selected as per Equation 4 for set C.

## 4. SEISMIC FRAGILITY OF STRUCTURES UNDER MS-AS SEQUENCES

### *4.1. Building model*

A four-story two dimensional and three-bay reinforced concrete (RC) special moment resisting space frame (SMRF) designed acoording to the provisions of ACI 318-02 and

ASCE 7-05 building model is considered in this study (Figure 2). Due to high ductility and energy dissipation capacity, an SMRF can sustain significant inelastic deformation before collapse. The building is designed for a site located in northen Los Angeles, California.

The beams and columns of the buildings are modelled as lumped plasticity beam-column elements in OpenSees (2018). The inelastic flexural springs at the ends of the beam-column element are modelled using material developed by Ibarra et al. (2005) that is capable of capturing strength and stiffness degradation over cycles of loading. The models follow a trilinear backbone curve characterised by elastic and post elastic capacity parameters that are calculated based on experimental studies conducted on more than 200 columns (Haselton et al. 2008). The elastic foundation rotational springs were also provided at the base to the bottom column. The detailed description of the building model can be found at Haselton et al. (2011).

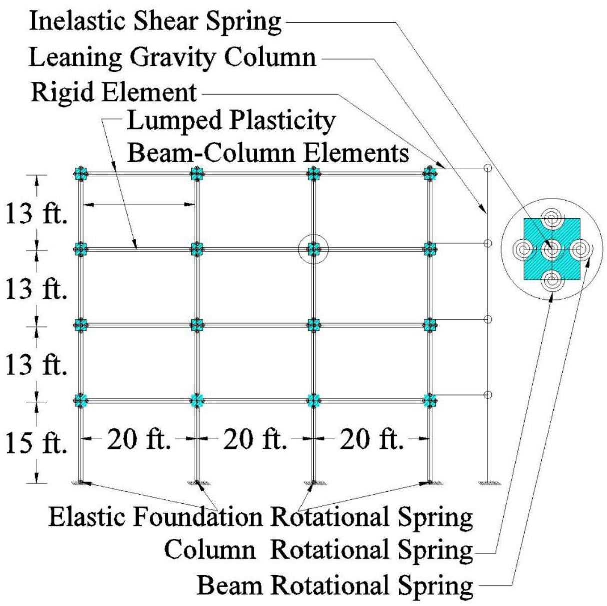


*Figure 2: Layout of the building model considered in the study*

### *4.2. Nonlinear dynamic analysis*

The seismic response of structure under multiple ground motion sequence sets is compared by implementing incremental dynamic analysis (IDA). In this procedure an earthquake ground motion is applied to the structure and its response is recorded using an engineering demand parameter (EDP) such as roof drift, maximum interstory drift and displacement ductility. After that, the ground motion is scaled and again the structural response is recorded. The procedure of scaling ground motions and recording response is continued until it results in the collapse of the structure. In this study, the intensity of ground motion is measured using spectral acceleration at fundamental time period, $Sa(T_1)$ and EDP is taken as maximum interstory drift ratio across all the floors. The collapse capacity of the structure is defined as the IM of the scaled MS-AS sequence that causes dynamic instability in the structure, indicated by an unbounded increase in the interstory drift ratio at any floor. This is in line with capturing side-sway collapse through which ductile reinforced concrete moment frames usually fail.

The incremental dynamic analysis is carried out for the four story building in the study using set A-F ground motion sequence sets detailed in Section 3. The scaling of earthquake records does not alter its central frequency, shape factor or maximum velocity to acceleration ratio and thus, preserves the relationship between frequency content of mainshock and aftershock at any level of scaling during IDA for each set of MS-AS sequences. The IDA procedure is used to determine a distribution of collapse capacities of the building, when subjected to different sets of MS-AS sequences, capturing the record-to-record variability associated with the sequences.

## 5. RESULTS

IDA results are used to develop collapse fragility curve for the building that represents the probability of collapse of a structure at different intensities of earthquake ground motion. The fragility curves are developed for the building model subjected to different sets of MS-AS sequences. The two main parameters which characterize a fragility curve are: (a) median collapse capacity and, (b) lognormal standard deviation. The median collapse capacity is defined as the intensity of ground motion that corresponds to 50% probability of collapse and lognormal standard deviation is a measure of variation in collapse capacity due to different sources of uncertainties. This study considers only record to record uncertainties in ground motion sequences, i.e. no two ground motions will be similar. The collapse fragility curve parameters are calculated for each set of MS-AS sequence and compiled in Table 2 and illustrated in Figure 3. The variation in the median collapse capacity for different sets of MS-AS sequences is also illustrated in Figure 4.

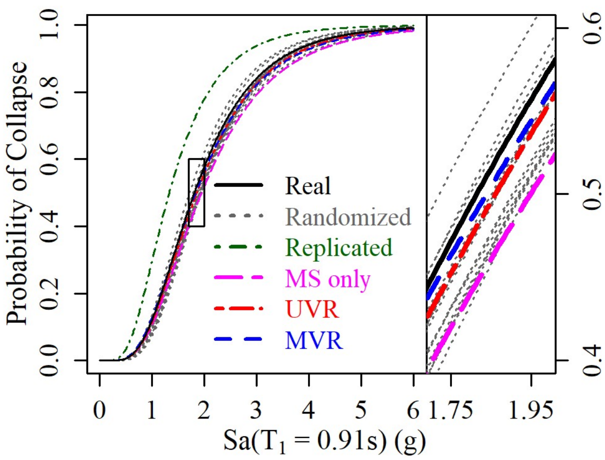


*Figure 3: Fragility curves in terms of Sa(T1) for different set of sequences for a four-story building model*

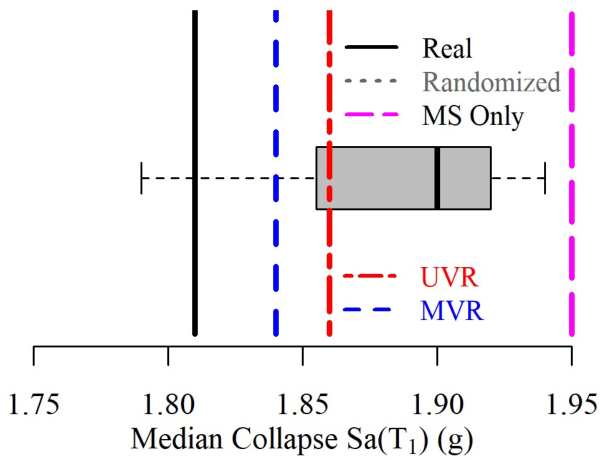


*Figure 4: Comparison of median collapse capacities for different sets of MS-AS sequences*

Based on Figure 3 and 4, following observations are made:

- The median collapse capacity corresponding to only MS earthquakes tend to be higher than other types of sequences and results in an overestimation of the actual capacity of the building models. This result is in accordance with the increased fragility of the structures when they are subjected to MS-AS sequences as compared to MS alone as observed in past research (Hatzivassiliou and Hatzigeorgiou 2015; Jalayer and Ebrahimian 2017; Jeon et al. 2015; Raghunandan et al. 2015; Ruiz-García and Negrete-Manriquez 2011; Song et al. 2014). The increased duration of shaking caused by aftershocks leads to an accumulation of damage over cycles of loading. The median collapse resistance capacity for Set F comprising only MS ground motions is 8% higher than Set A consisting of real as-recorded MS-AS sequences.
- The left shift in the fragility curve for replicated set of MS-AS sequences (Set D) in Figure 3 is more apparent than any other set of MS-AS sequences. The large intensity MS being repeated as an aftershock results in a significant underestimation of structure collapse capacity. Here, the collapse capacity due to replicated sequences is 27% lower as compared to the real MS-AS sequences (Set A). The replicated sequences prove to be more damaging at even low level of intensities, as evident from collapse fragility curves in Figure 3. Therefore, it is recommended not to use replicated sequences in determination of structural response.
- The boxplot in Figure 4 represents a distribution of collapse capacity estimated by fifteen sets of randomized sequences. A line dividing the boxplot in two parts is the median of fifteen data points. As seen from Figure 4, the median collapse capacity of sets E1 to E15 varies from the median collapse capacity of real MS-AS sequences in the range -5% to +7% and the range of variation depends on the MS-AS sequences randomly simulated. As observed from the boxplot, in most instances,

randomized sequence sets underestimate the capacity of a four-story building model, which need not be the case always. Running a large number of MS-AS random sequences can aid in predicting median collapse capacity closer to the one predicted using real Set A.

- The artificial sequences generated using univariate and multivariate linear regression analysis gives the median collapse capacity quite close to the original value. As compared to real MS-AS sequences, the median collapse capacity predicted by the UVR Set B is 2.6% lower than the real Set A for the considered building model. In the same manner, the collapse capacity estimated by employing artificial sequences of MVR Set C is 1.3% lower than the one from real Set A. MVR Set C predicts the real median collapse capacity better than UVR Set B of sequences for the building model considered in the study. Set B and Set C are better predictors of median collapse capacity as compared to other MS-AS simulation techniques such as Set D and E.
- In addition to the median collapse capacity, the sequences set B and C also captures the record to record variability associated to real sequences quite closely. The median collapse capacity and lognormal standard deviation for different sets of MS-AS sequences is provided in Table 2.

*Table 2: Fragility parameters for different sets of MS-AS sequences in terms of Sa ($T_1$) (g)*

| *Set* | *Set Details* | $x_m$[1] | *% change*[2] | $\beta$[3] |
|---|---|---|---|---|
| *A* | *Real* | *1.81* | *0%* | *0.51* |
| *B* | *UVR* | *1.86* | *2.6%* | *0.51* |
| *C* | *MVR* | *1.84* | *1.3%* | *0.53* |
| *D* | *Replicated* | *1.33* | *-27%* | *0.53* |
| *E1 to E15* | *Randomized* | *1.72-1.94* | *-5% to +7%* | *0.45-0.53* |

[1] *Median collapse capacity in terms of Sa ($T_1$)*
[2] *Percentage change in in $x_m$ as compared to Set A*
[3] *Log-normal standard deviation*

## 6. CONCLUSION

This study presents a new approach of generating artificial MS-AS sequences that explicitly takes into account the relationship between parameters of mainshock and an aftershock. Instead of relying on the random combination of mainshock events to generate artificial MS-AS sequences, an intelligent selection of aftershocks can be made with reduced degree of uncertainty in structural response estimation. The proposed methodology can also provide a useful basis in evaluation of realistic post aftershock collapse capacity and evacuation decisions for the damaged structure. The building model is subjected to different generated sets of MS-AS sequences namely real, replicated, randomized, UVR and MVR. Based on analysis results, collapse fragility is computed for different sets of artificial MS-AS sequences and compared with the fragility obtained using real set of MS-AS sequences. It was observed that UVR and MVR approaches, which considers a relationship between the MS and AS ground motion parameters while generating sequential ground motions, predict median collapse capacity and lognormal standard deviation similar to the real MS-AS sequences.

The proposed methodology provides a simple means for selecting MS-AS sequences when aftershock hazard data is not available. The proposed methodology needs to be further validated in future for other types of earthquakes and different structures.

## 7. ACKNOWLEDGEMENT

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## 8. REFERENCES

ACI. Building code requirements for structural concrete (ACI 318-02). American Concrete Institute: Farmington Hills, MI." (2002).

ASCE. Minimum design loads for buildings and other structures (7-05), Reston, VA." (2005).

Boore, D. M., and Akkar, S. (2003). "Effect of causal and acausal filters on elastic and inelastic response spectra." *Earthquake Engineering & Structural Dynamics*, 32(11), 1729–1748.

Gaetani d'Aragona, M., Polese, M., Elwood, K. J., Baradaran Shoraka, M., and Prota, A. (2017). "Aftershock collapse fragility curves for non-ductile RC buildings: a scenario-based assessment." *Earthquake Engineering & Structural Dynamics*, 46(13), 2083–2102.

Haselton, C. B., Liel Abbie B., Deierlein Gregory G., Dean Brian S., and Chou Jason H. (2011). "Seismic Collapse Safety of Reinforced Concrete Buildings. I: Assessment of Ductile Moment Frames." *Journal of Structural Engineering*, 137(4), 481–491.

Haselton, C., Liel, A., Lange, S., and Deierlein, G. "PEER Report 2007/03 Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings. Pacific Earthquake Engineering Research Center: Berkley, CA, 2008."

Hatzivassiliou, M., and Hatzigeorgiou, G. (2015). "Seismic sequence effects on three-dimensional reinforced concrete buildings." *Soil Dynamics and Earthquake Engineering*, 72.

Ibarra, L. F., Medina, R. A., and Krawinkler, H. (2005). "Hysteretic models that incorporate strength and stiffness deterioration." *Earthquake Engineering & Structural Dynamics*, 34(12), 1489–1511.

Jalayer, F., and Ebrahimian, H. (2017). "Seismic risk assessment considering cumulative damage due to aftershocks." *Earthquake Engineering & Structural Dynamics*, 46(3), 369–389.

Jeon, J.-S., DesRoches, R., Lowes, L. N., and Brilakis, I. (2015). "Framework of aftershock fragility assessment–case studies: older California reinforced concrete building frames." *Earthquake Engineering & Structural Dynamics*, 44(15), 2617–2636.

Kramer, S. (1996). "Geotechnical Earthquake Engineering". Prentice-Hall.

Lee, K., and Foutch, D. A. (2004). "Performance Evaluation of Damaged Steel Frame Buildings Subjected to Seismic Loads." *Journal of Structural Engineering*, 130(4), 588–599.

OpenSEES. (2018). "Open System for Earthquake Engineering Simulation." *Pacific Earthquake Engineering Research Center, Univ. of California, Berkley, CA,* <http://opensees.berkeley.edu/index.php>

Raghunandan, M., Liel, A. B., and Luco, N. (2015). "Aftershock collapse vulnerability assessment of reinforced concrete frame structures." *Earthquake Engineering & Structural Dynamics*, 44(3), 419–439.

Robertson, J., and Koontz, H. (2015). "Magnitude 7.8 Earthquake in Nepal & Aftershocks." U.S.G.S., May 12, 2015.

Ruiz-García, J., and Negrete-Manriquez, J. C. (2011). "Evaluation of drift demands in existing steel frames under as-recorded far-field and near-fault mainshock–aftershock seismic sequences." *Engineering Structures*, 33(2), 621–634.

Song, R., Li, Y., and van de Lindt, J. W. (2014). "Impact of earthquake ground motion characteristics on collapse risk of post-mainshock buildings considering aftershocks." *Engineering Structures*, 81, 349–361.

Vanmarcke, E. H. (1976). "Structural response to earthquakes." *Seismic Risk and Engineering Decisions*, Elsevier, Amsterdam, 287–338.